In-Space Transportation Capability Roadmap Development

IST CRM Team Presentation to:
Robotic and Human Exploration of
Mars Strategic Roadmap Committee
February 8, 2005

Scope and Summary

- **Develop the capability roadmaps for In-Space Transportation that are required to support the Vision for Exploration (non-nuclear)**
  - Orbit-to-orbit transportation
  - Any necessary in-space transfer
  - Includes
    - Potential synergy with upper stage
    - Descent propulsion
    - Planetary ascent
  - Special emphasis on:
    - In-space main engine
    - Cryofluid management
    - AR&D and vehicle autonomy
    - Aerocapture, solar sails, low power EP
- **Planning treats capabilities as elements / stages of a system**
- **Planning must be consistent with the Exploration spirals and science mission schedules**

In-Space Transportation Capability Roadmap Team

♦ Dr. Paul McConnaughey	NASA / MSFC (chair)
♦ Col. Joe Boyle	USAF / SMC (co-chair)
♦ Mr. Pete Vrotsos	NASA / HQ
♦ Mr. John Connolly	NASA / HQ
♦ Mr. Rick Ryan	NASA / MSFC
♦ Dr. Tim Crain	NASA / JSC
♦ Mr. Mike Meyer	NASA / GRC
♦ Dr. Russ Partch	AFRL / VSE
♦ Mr. Alan Sutton	AFRL / PRSE
♦ Mr. Ron Reeve	NASA / JPL
♦ Dr. Ted Johnson	NASA / LaRC
♦ Dr. Jesse Leitner	NASA / GSFC
♦ Dr. Shamim Rahman	NASA / SSC
♦ Mr. Nick Johnston	NASA / MSFC
♦ Dr. Mike Watson	NASA / MSFC

Consulting / Eng.Support

♦ Ms. Carol Covell	MSFC / Jacobs Eng.
♦ Mr. Brand Griffin	MSFC / Gray Research

IST CRM Team Advisors / Consultants

- **Academia**
  - Dr. Bob Santoro
  - Dr. Norman Fitz-Coy
  - Dr. Clark Hawk
  - Dr. John Olds
  - Dr. Carlos Cesnik
  - Dr. Mark Lewis
  - Penn. State University
  - Univ. of Florida
  - Univ. of Alabama, Huntsville
  - Georgia Inst. Tech.
  - Univ. of Michigan
  - Chief Scientist, USAF

- **Industry**
  - Boeing
  - Lockheed/Martin
  - Northrop/Grumman
  - Aerojet
  - Pratt and Whitney
  - Rocketdyne
  - SAIC
  - Northrop/Grumman Space Tech.

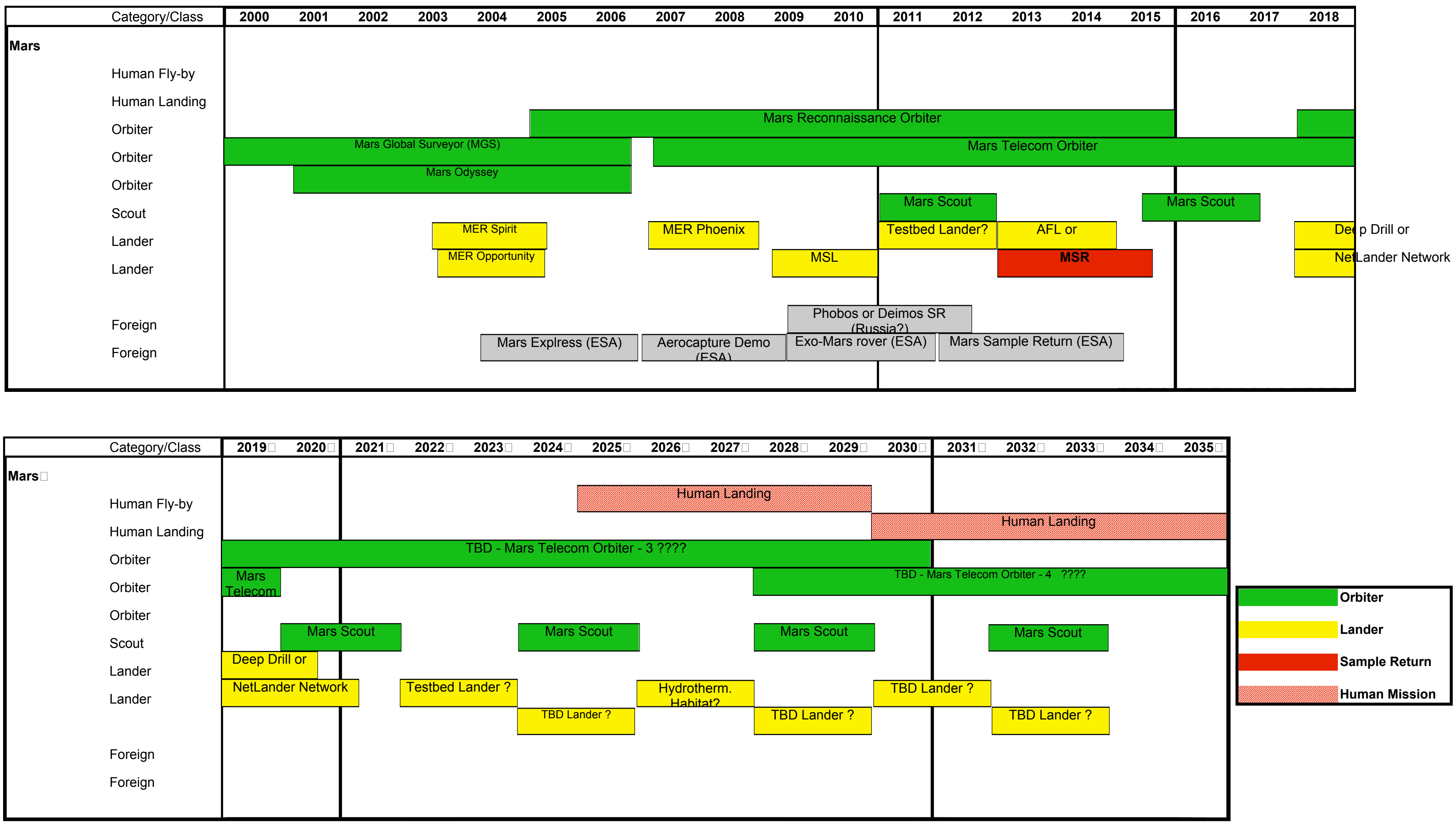
In-Space Transportation CRM Team Plan / Approach

- **Previous and current studies reviewed for applicability**
  - CRAI
  - 120-day Study
  - SLI Planning studies and technology maturation results
  - HR&T, intramural, and extramural awards
  - IISTP
  - Available architecture studies
- **Review of requirements**
  - DRM's, DRA's, Framework, ConOps
    - ESMD missions
    - Science missions
    - Framework matrix generated by APIO
- **WBS/CBS structure by which to build planning activities**
  - Content will be under configuration control
- **Roadmap planning activities by team**
  - Mapping of previous study results to WBS / CBS
  - Gap identification / analysis / fill-in
  - Roadmaps, subsystem roadmaps, supporting quad charts
- **Plan to TRL 6+, integrate into spiral schedules and science regimes**
- **First draft presentation to the NRC in early April**

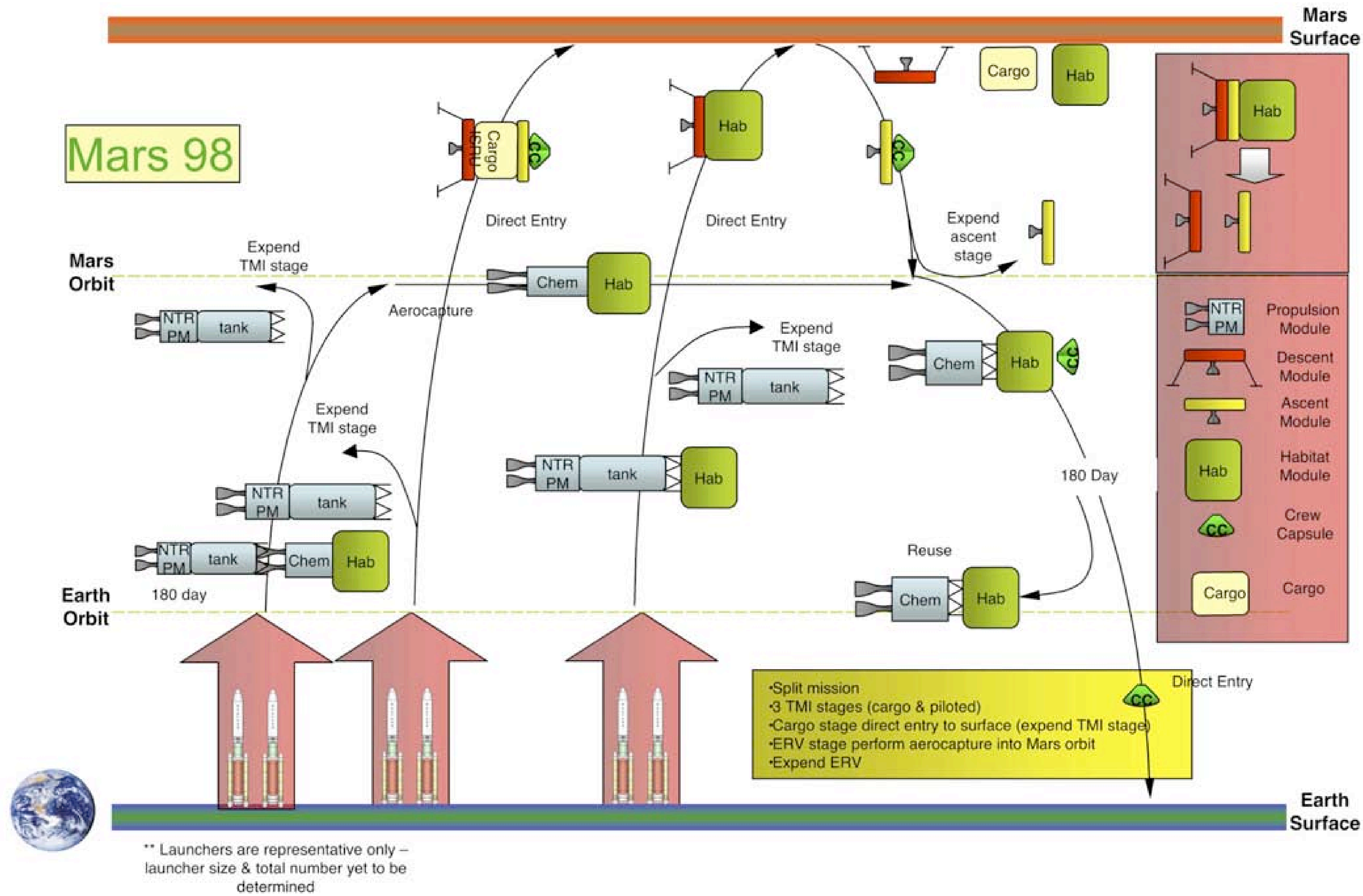
Capability Breakdown Structure

- Dr. Paul McConnaughey, NASA Chair
  Col. Joe Boyle, USAF Co-Chair
  - GN&C / AR&D Subteam – Dr. Jesse Leitner
  - Structures Subteam – Dr. Ted Johnson
  - Chemical Propulsion Subteam – Rick Ryan
  - Non-Chemical Propulsion Subteam – Ron Reeve
  - Thermal Systems Subteam – Mike Meyer
  - Avionics Subteam – Dr. Mike Watson
  - TVC / Docking / Sep Sys Subteam – Nick Johnston
  - Enabling Test Capability Subteam – Shamim Rahman

Mars Mission Timeline



Mars Architecture Example



Example Capability Breakdown Structure Integrated to the Science Missions

REGIME	ROBOTIC MISSION	Launch or IOC	Trans Stage[1] Chem	Trans Stage[1] SE	Trans Stage[1] SS	Trans Stage[1] NE	Descent[2]	Landing[2]	Ascent[3]	Secondary Control[4] Chem	Secondary Control[4] SE	Secondary Control[4] SS	Secondary Control[4] NE	CFM[5]	AR&D[6]	SMD Mission 11/23/04	Chart # *
R2 Inner Planets	*Comet Surface Sample Return*	*<2013*					Chem	Chem	Chem	chem	EP/ chem	vanesc p-cm		Chem	Enabling	Comet Surface Sample Return	9, 20
	Comet Sample Return (No Landing)						NA	NA	NA		EP/ chem	vanesc p-cm				Comet Internal Struct. Deep Impact	8
	Venus In Situ Explorer	*<2013*					Chem	Chem	NA	chem				Chem		Venus In Situ Explorer	9, 17
	Venus Sample Return	*<2013*					Chem	Chem	Chem	chem	EP/ chem	vanesc p-cm	EP/ chem	Chem/NE	Enabling	Venus sample return	17
	E/S L1 Diamond	*2015-2028*					NA	NA	NA		EP/ chem	vanesc p-cm					
	Mars Orbiters						NA	NA	NA	chem		vanesc p-cm		Chem		Mars Telesat Obiter, MRO	6, 16
	Mars Sample Return	*<2010*					Chem	Chem	Chem	chem	EP/ chem	vanesc p-cm		Chem	Enabling	Mars Sample Return	7, 16
	Venus Aeronomy Probe (VAP)						NA	NA	NA	chem	EP/ chem	vanesc p-cm		Chem		Venus Atm Samples	16
	Mars Aerobot (Balloon/Airplane)						NA	NA	NA	chem				Chem		Scout	7
	Phobos Sample Return						Chem	Chem	Chem	chem	EP/ chem	vanesc p-cm		Chem	Enabling		
	Mars Aeronomy Probe						NA	NA	NA	chem		vanesc p-cm		Chem			
	Pole Sitter						NA	NA	NA		EP/ chem	vanesc p-cm					
	Magnetospheric Constellation						NA	NA	NA	chem	EP/ chem			Chem			
	Geosynchronous/ Other HEO Earth Observation						NA	NA	NA	chem	EP/ chem			Chem			
	High Orbit Microgravity Platforms						NA	NA	NA	chem	EP/ chem	vanesc p-cm		Chem			
	Lunar South Pole Aitken Basin Sample Return						Chem	Chem	Chem	chem				Chem	Enabling	Aitken Basin	9
R4 Near Sun	*Solar Polar Imager*						NA	NA	NA	chem	EP/ chem	vanesc p-cm		Chem			
	Telemachus									chem	EP/ chem	vanesc p-cm		Chem			
	Solar Probe									chem	EP/ chem	vanesc p-cm		Chem			
	Mercury Sample Return						Chem	Chem	Chem	chem	EP/ chem	vanesc p-cm	EP/ chem	Chem/NE	Enabling	Mars Sample Return	17
	Heliospheric Imager & Galactic Observer						NA	NA	NA		EP/ chem	vanesc p-cm					
	Inner Heliosheric Sentinels						NA	NA	NA		EP/ chem	vanesc p-cm					
R6 Outer Planets	*Jupiter Polar Orbiter with Probes*									chem	EP/ chem	vanesc p-cm	EP/ chem	Chem/NE		Jupiter Orbiter	9, 19
	Jupiter Icy Moons Orbiter (JIMO)												EP/ chem	EP		JIMO	19
	Europa Lander									chem	EP/ chem		EP/ chem	Chem/NE		Dedicated Europa Lander	19
	Io Electrodynamics									chem	EP/ chem	vanesc p-cm		Chem			
	Saturn Ring Observer									chem	EP/ chem	vanesc p-cm	EP/ chem	Chem/NE		Saturn Ring Observer	19
	Titan Explorer									chem	EP/ chem	vanesc p-cm	EP/ chem	Chem/NE		Titan Explorer	19
	Neptune Orbiter									chem	EP/ chem		EP/ chem	Chem/NE		Neptune Orbiter	19
	Titan Sample Return						Chem	Chem	Chem	chem	EP/ chem		EP/ chem	Chem/NE	Enabling		
R8 Beyond Planetary System	*Interstellar Probe*									chem		vanesc p-cm	EP/ chem	Chem/NE			
	Ultra-High Delta-V Small Payload											vanesc p-cm	EP/ chem	EP			
32 science missions																Main-belt asteroids DAWN	8
Notes/Assumptions:																Pluto Kuiper Belt	9, 10, 18
	Green- Studied, Good Use		18	14	6	6	44			25	24	23	11	27	7	Mercury Lander	17
	Blue- Positive, needs Study		7	10	17	5	39									Deep Drill	17
			25	**24**	**23**	**11**	**83**									NetLander Network	17
																Europa Deep Impact	19
																Neptune Orbiter w/ Probes	19
																Mars Telecom Orbiter	17
																JUNO	18
																Uranaus Orbiter w/ Probes	19
																DAWN	20
																Deep Impact	20
																Ambassador (main belt asteriod)	20

1 All earth-return stages use the same propulsion as the outbound stage
2 Descent and landing use chemical propulsion for the purposes of technology identification (actual missions may use non-chemical techniques)
3 All ascent propulsion is chemical
4 Matches secondary propulsion to Trans stage propulsion
5 Cryo Fluid Management (CFM) for chemical and Nuclear Electric propulsion
6 Autonomous Rendezvous & Docking (AR&D) enabling for all sample return missions

* Science Mission Directorate and Solar System Exploration Division Solar System Explortion Technology Program, Nov. 23, 2004

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Mars Missions / Capability Needs Matrix

Capability Needs by Mission	MSL 2009	Mars Scout (Multiple) 2011	Testbed Lander (Multiple) 2011	Sample Return 2014	Deep Drill 2018	Net lander 2018	Spiral 4 Human Fly-by	Spiral 5 Humans on Mars
1.0 In-Space Transportation Elements/Capability Needs								
2.0 Human Exploration Mission Elements/Capability Needs (SEE PREVIOUS SHEET)								
3.0 Robotic Science and Exploration Mission Elements/Capability Needs								
3.1 Robotic Space Craft Earth Departure Stage								
3.1.01 Integration Structure and Components								
3.1.02 GN&C/AR&D								
Guidance								
Navigation and Attitude Determination								
Control								
Simulation Tools								
3.1.03 Structures								
Propellant Tanks								
Primary Structures								
Secondary Structures								
Advanced Materials								
3.1.04 Propulsion Systems (Chemical)								
Main Engine								
Auxillary Propulsion Systems								
Main Propulsion System (including Propellant Pressurization System)								
3.1.04 Propulsion Systems (Non-Chemical)								
Low Power Electric Propulsion								
Aeroentry, Aerobraking and Aerocapture Systems								
Solar Sails								
Precision/ACS Propulsion								
Tethers								
3.1.05 Thermal Systems								
Cryogernic Fluid Management System								
Spacecraft Thermal Control (Place holder)								
3.1.06 Avionics								
Intelligent Integrated Vehicle Management								
Electrical Power System								
3.1.07 TVC System								
Actuators								
Power Supply								
3.1.08 Docking and Separation Systems								
Docking Adapter								
Separation Motors								

In Process

In-space Transportation Capability Needs for Mars Mission - Summary

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- **Autonomous Rendezvous and Docking (AR&D)**
- **Autonomous Vehicle Mission Manager**
- **Long-term Cryogenic Fluid Management**
- **Delta V for planetary escape and orbit insertion**
  - Aerocapture
  - In-space Chemical Engine(s)
    - Depends on nuclear/ISRU trade results/decision
  - High Isp Electric Propulsion
- **Ascent capability for sample return and humans**
- **Other Issues**

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In-space Transportation Capability Needs for Mars Mission

- **Autonomous Rendezvous and Docking**
  - Critical to Mars robotic and human missions
  - Required autonomy due to latency is key driver for Mars missions
  - Reverse contamination prevention for sample return
- **Mission / Need date for Full Scale Development**
  - Mars Sample Return (2010)
  - Lunar Mission Spiral II (2011)
- **Current capability**
  - No demonstrated US system
  - Russian system failure probability estimate by SAIC is 1 in 630
  - DART flight in 3-05 (rendezvous)
  - XSS-11 flight in 3-05 (satellite rendezvous, inspection, circumnavigation)
  - Orbital Express flight 6-06 (AR&D with refueling)
  - Reliable AR&D at system level not demonstrated
- **Capability gap closure**
  - 3-4 years with sufficient support

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In-space Transportation Capability Needs for Mars Mission

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- **Autonomous Vehicle Mission Manager**
  - Critical for elements with:
    - Significant Communications Latencies
    - Complex, Short Term Precision Operations (i.e. rendezvous and docking, precision landing, quick long distance transversal)
    - High Mission Reliability (Limited Opportunity Science, Human Missions)
- **Mission / Need date for Full Scale Development**
  - Mars Sample Return (2011)
  - Lunar Mission Spiral II (2012)
- **Current capability**
  - Robotic
    - High Level Problem Detection placing system in a dormant state
    - Requests Earth-based ground system corrections (High Response Latency)
  - Human
    - Ground Based, Procedure-oriented with limited automation of mission planning, diagnostics
- **Capability gap closure**
  - 5-7 years to close with focused program to develop
  - Automate Ground Systems
  - Migrate to Onboard Systems
  - Demonstrate in hybrid operational modes (full onboard autonomy with some ground or flight crew approval) on early missions

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In-space Transportation Capability Needs for Mars Mission

- **Long term Cyrogenic Fluid Management**
  - For cryofluid acquisition and storage for months/years in space
  - For NTP and Cryo-chemical missions to Mars
  - LH2, LO2, LCH4
- **Mission / Need date for Full Scale Development**
  - LOX/ LCH4 acquisition (LADs) and zero boil-off: Spiral I (2009)
  - LH2 acquisition: Spiral II EDS (2011)
  - LH2 zero boil-off storage: Spiral III of Lunar mission (2013)
- **Current capability**
  - Propulsive settling for fluid acquisition; storable OMS/RCS
  - 10 hours on a Centaur upperstage
  - No flight-qualified cryocoolers at 20 K (LH2)
- **Capability gap closure**
  - 4-7 years with sufficient support
  - Flight demonstration required for LADS

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In-space Transportation Capability Needs for Mars Mission

- **Delta V for Planetary Escape and Orbit Insertion**
  - Aerocapture
  - In-space Chemical Engine(s) (Depends on nuclear/ISRU trade results/decision)
  - High Isp Electric Propulsion
- **Mission / Need date for Full Scale Development**
  - Aerocapture and Chemical Engine(s) applicable to all Mars orbiters and MSR (2010)
  - High Isp EP enables MSR on single LV, provides higher latitude surface access
  - Chemical engine needed in Spiral II Lunar (2009)
- **Current capability**
  - Aerocapture
    - TRL ~ 6 for low-L/D Mars & TRL ~ 4 for mid-L/D Mars
  - In-space Chemical Engine(s)
    - Hypergolic Pressure-fed Storable Propulsion Systems (~6 klbf thrust)
    - RL-10 in-space Pump-fed LO2/LH2 engine (22 - 25 klbf thrust)
  - EP - 3200 sec Isp for Ion engines
- **Capability gap closure**
  - Aerocapture 3-4 years with sufficient support
  - In-space Chemical Engine(s) 7-9 years with sufficient support
  - EP - 4-6 years with sufficient support

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In-space Transportation Capability Needs for Mars Mission

- **Ascent capability for sample return and humans**
  - Need highly reliable propulsion (human rated for 2030) and launch platform
  - Propellant choice base on system trades
    - Hypergolic/storable
    - Solid motor
    - Cryogenic
  - Launch platform determined by landing approach
    - Airbags
    - Pedestal/platform
- **Mission / Need date for Full Scale Development**
  - Mars Sample Return (2009)
- **Current capability**
  - Propulsion element needs development
  - Launch experience for platforms only (Apollo)
- **Capability gap closure**
  - 4-6 years with sufficient support

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Other In-space Transportation Capability Issues for Mars Mission (applies to numerous CRM'S)

- Component life
- Assembly interface automation
- Long-term intermittent usage, space storage, and reliability for subsystems
- Radiation degradation of materials (TPS, insulation, etc.)
- Weight

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Backup

CFM Rationale/back-up

Mission Need dates:
LDRM-2 identifies LOX/CH4 for CEV and identifies cryocoolers => implies zero boil-off (ZBO); technology for LOX/CH4 flight cryocoolers is close now (TRL 6+) so I think the shorter end of FSD (4 yrs) is O.K.

Acquisition: Propulsive settling could be functional for main propulsion, but LADs are required for RCS/OMS (many firings, omni-g environment), I put the need for LH2 LADs into spiral II but am having trouble confirming baseline RCS fuel (this is PRELIMINARY)

ZBO of LH2 is probably enhancing for Spiral II duration missions (mass penalty but workable) but enabling for Mars missions => I drew the line of needing it for Spiral III

SOA:
Propulsive settling used by Centaur and I believe it was demonstrated in a Saturn upper stage; LAD's are used for storables on spacecraft but no cryo experience

The key drivers for cryocoolers are cold head temperature (LOX much easier than LH2), heat removal capacity (cooling power), efficiency (input power/cooling power) so you can afford to run it (currently ~300:1 for LH2 temperatures and small non-flight systems)

Gap closure:

FSD of LADs can probably be accomplished in 4 years, there is uncertainty on life qualification approach for a cryocooler so more wiggle room required there

The Cryo Working Group has agreed that cryo LADs need to be proven in zero-g

In-space Transportation Capability Needs for Mars Mission

- **Aerocapture**
  - Propellant-less insertion to a precision orbit via aerodynamic drag
    - Low-L/D aeroshells suffice for small and medium robotic missions
    - Mid-L/D aeroshells required for large robotic or human missions
  - Critical to Mars robotic and human missions
- **Mission / Need date for Full Scale Development**
  - Generally applicable to all Mars orbiters, with earlier practical infusion starting in the 2011 time frame
  - Potentially applicable to Mars Sample Return (2010)
- **Current capability**
  - TRL ~ 6 for low-L/D Mars aerocapture
  - TRL ~ 4 for mid-L/D Mars aerocapture
- **Capability gap closure**
  - Risk adverse science mission posture leads to the need for a flight test experiment of low L/D aeroshell technology (e.g., ST-9?)
  - Subsequent mid L/D development is 3-4 years with sufficient support

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In-space Transportation Capability Needs for Mars Mission

- **High Isp Electric Propulsion**
  - Needs beyond NSTAR ion engine
  - 4200-5000 sec Isp, with increased throughput
  - Enables MSR on single LV, provides higher latitude surface access, supports return of sample to LEO
- **Mission / Need date for Full Scale Development**
  - Mars Sample Return (2011)
- **Current capability**
  - 3200 sec ISP for ion engines
- **Capability gap closure**
  - 4-6 years with sufficient support

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In-space Transportation Capability Needs for Mars Mission

- **Chemical In-space Engine**
  - Need reliable long-life in-space engine (human rated)
  - Need based on chemical/nuclear decision for Mars
  - Propellant choice base on system/launch vehicle / ISRU trades
- **Mission / Need date for Full Scale Development**
  - Spiral II / III Lunar mission LO2/LH2 Earth Departure Stage (2007)
  - Spiral III Lunar mission LO2/CH4 CEV Service Module, Lander Ascent / Descent Stages (2014) as precursor to Mars
- **Current capability**
  - Hypergolic Pressure-fed Storable Propulsion Systems (~6 klbf thrust)
  - RL-10 in-space Pump-fed LO2/LH2 engine (22 - 25 klbf thrust)
- **Capability gap closure**
  - 7-9 years with sufficient support

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Draft Chemical Propulsion Roadmap

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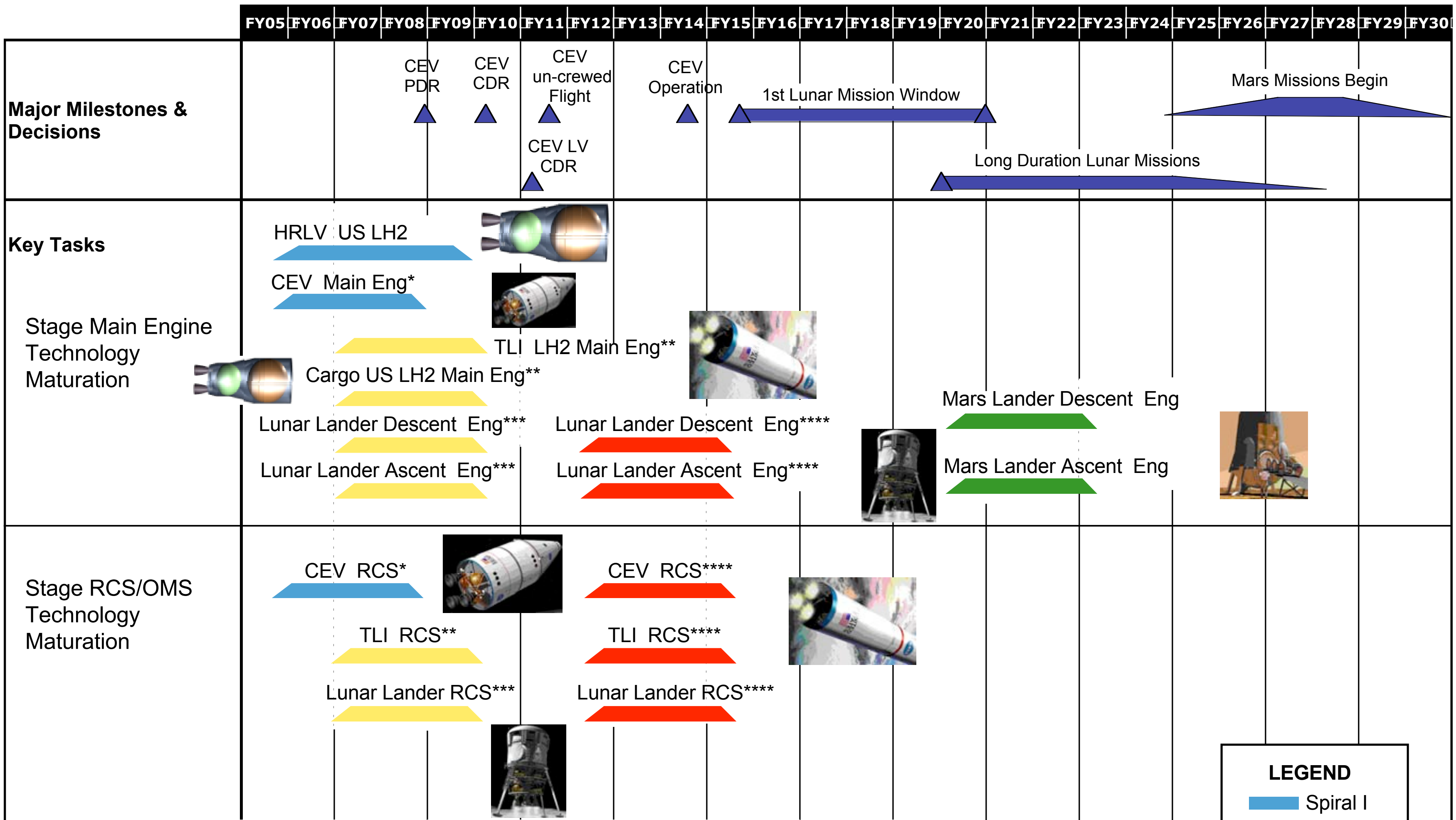
ESMD Human Mission Technology Needs



NOTES:

* Required only if using non toxic cryogenic propellants

** Required only if engine different from HRLV US

*** Required only if using non toxic cryogenic propellants and engines different from CEV

**** Required only if not developed in Spirals I & II and needed as precursor to Spirals IV & V

Draft In-Space Avionics Roadmap

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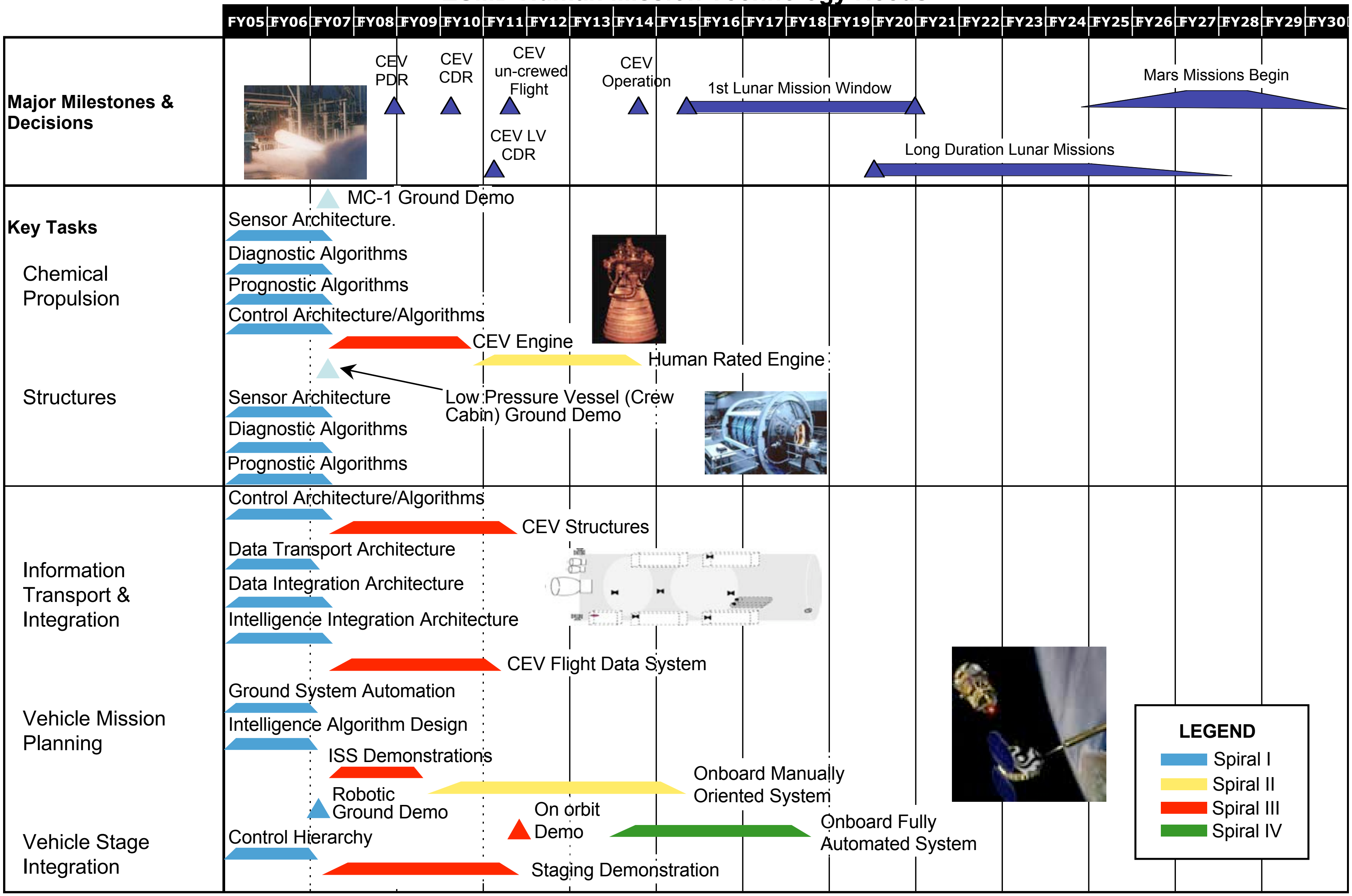
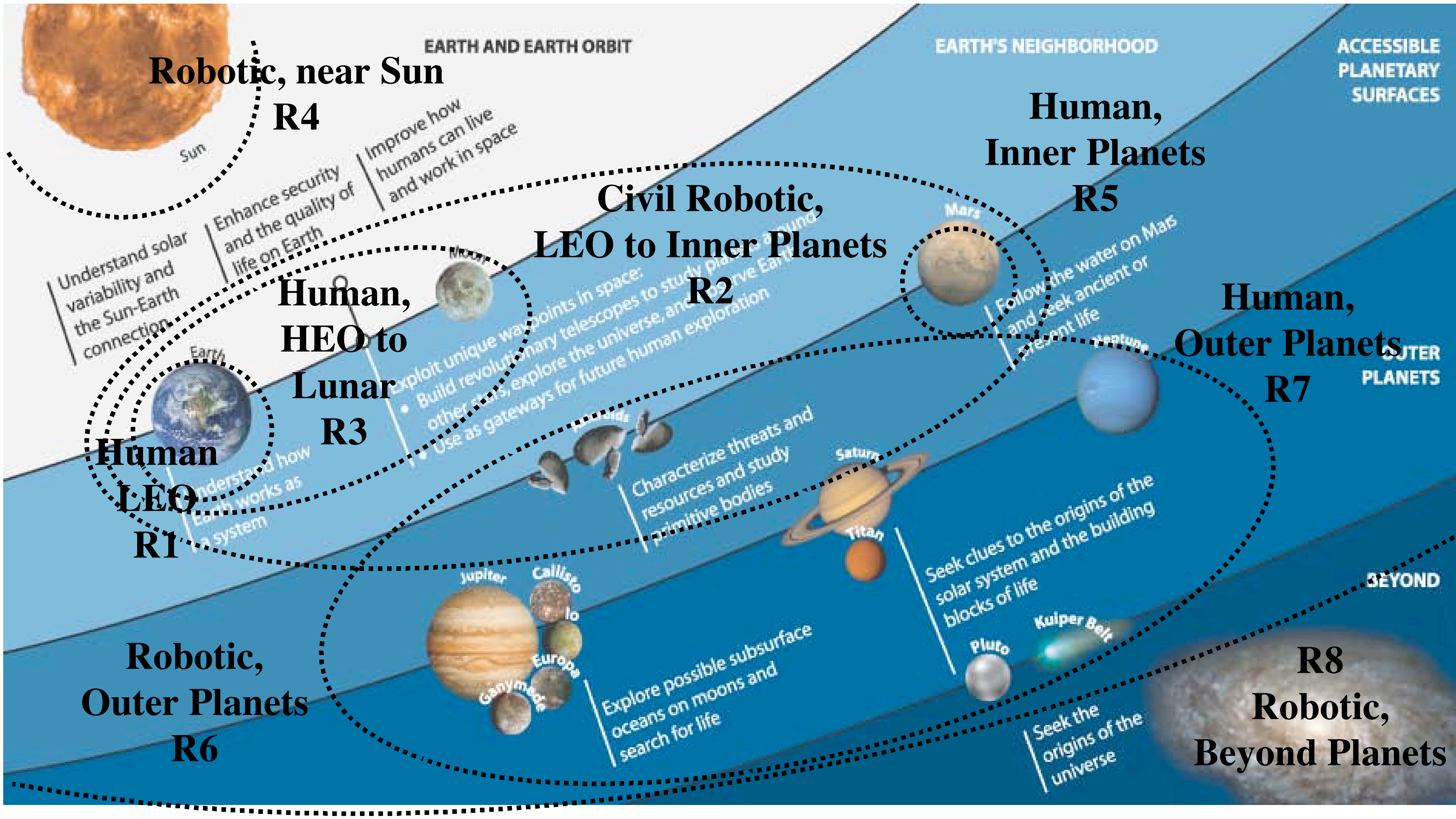
ESMD Human Mission Technology Needs



Relevance - Regimes Based on Common In-space Transportation Capability Requirements

Stepping Stones Overlay on Space Transportation Regimes



In-Space Transportation is a fundamental capability required to enable all aspects of Exploration Vision